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AIRCRAFT COLOR DISPLAYS: CHROMATICITY AND LUMINANCE REQUIREMENTS

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Color coding of aircraft display information, when used properly, can decrease the pilot's workload in performing certain visual tasks. In order to be effective, the luminance levels and chromaticity coordinates (with limits) need to be specified. This report provides human factors design guidelines for developing color display criteria. The issues addressed include luminance contrast, color differences, sunlight ambient illumination, and chromaticity recommendations.

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INTRODUCTION

In order to increase the visual perception of display information, many new and modified aircraft are currently being equipped with color displays. Color adds another information coding dimension to those already used such as shape, shading, size, and blinking. With the proper use of color coding, information can be quickly sorted into categories by the operator.

Figure 1 shows the gamut of possible colors that are perceptible by the average human. These colors are presented on the C.I.E. (Commission Internationale de l'Eclairage) chromaticity diagram which is a two dimensional representation of all colors as a function of the relative proportions of the three primaries, red, green, and blue (x, y, and z respectively). The z axis is not shown, but it is equal to 1-(x+y). Chromaticity is the measure of both hue and saturation. Hue is related to the wavelength of the color and is represented by the position of the color around the outline (spectrum locus) of the diagram. The numbers around the diagram are the dominant wavelengths of the colors given in nanometers. Saturation is represented by the relative distance from the center or equal energy point (x = .333, y = .333) to the spectrum locus. The spectrum locus represents the locations of the most saturated colors. Chromaticity does not include the luminance of the color. Figure 2 shows another chromaticity diagram which is a linear transformation of x, y into u', v'. This diagram is called the Uniform Chromaticity Scale (U.C.S.), and it is an improvement in perceptual uniformity over the C.I.E. diagram. This means that equal distances in the color space represent nearly equal changes of perception in chromaticity. The color labels for the areas within each diagram are the designations developed by Kelly (1943). The additive primary colors are red, green, and blue. The subtractive primary colors are cyan (greenish blue), magenta (purple), and yellow. Throughout this report, the additive primaries (and white) will be printed in upper case on the figures, and the subtractive primaries and all other colors will be printed in lower case.

LUMINANCE, LUMINANCE CONTRAST AND BRIGHTNESS

Besides chromaticity, another important measurement of color is luminance which is related to the perception of brightness. Luminance is measured in foot-Lamberts (fL) or candelas per square meter (nits). Table 1 shows some representative calculations based solely on the luminances of the various primary colors and the reflected display background. These calculations, as well as the calculations shown on the other tables, were performed using the LOTUS 1-2-3 spreadsheet. The equations for these spreadsheets can be obtained from the author. For a complete explanation of the background luminance, contrast ratio, shades, and modulation values shown in Table 1 refer to Breitmaier (1987). The bottom of Table 1 shows the transformations of the chromaticity coordinates from x, y space to u', v' space. The column labeled "SATURATN" presents values which are simply the linear distances of the chromaticity coordinates from the equal energy point. The larger the number, the more saturated (less white) the color.

Table 2 relates the two measures of color: chromaticity and luminance. Chromaticity is entered in x, y coordinates. Using a conversion function described by Cowan and Ware (1987), two values are calculated. The first value gives the brightness of the color compared to the luminance of white. For example, a green stimulus will appear to have less brightness than white even though the luminances are the same value. On the other hand, a blue stimulus will appear to be brighter than a white with the same luminance. These relative brightness values are presented in the column labeled "Br". The second value gives the luminance required for a color to equal the brightness of white that is at 100 fL. These luminance values are presented in the column labeled "Lreq". Figures 3 and 4 graphically present the Br and Lreq values respectively. When attempting to differentiate or equalize colors in brightness appearance, this luminance/brightness conversion function should be used.

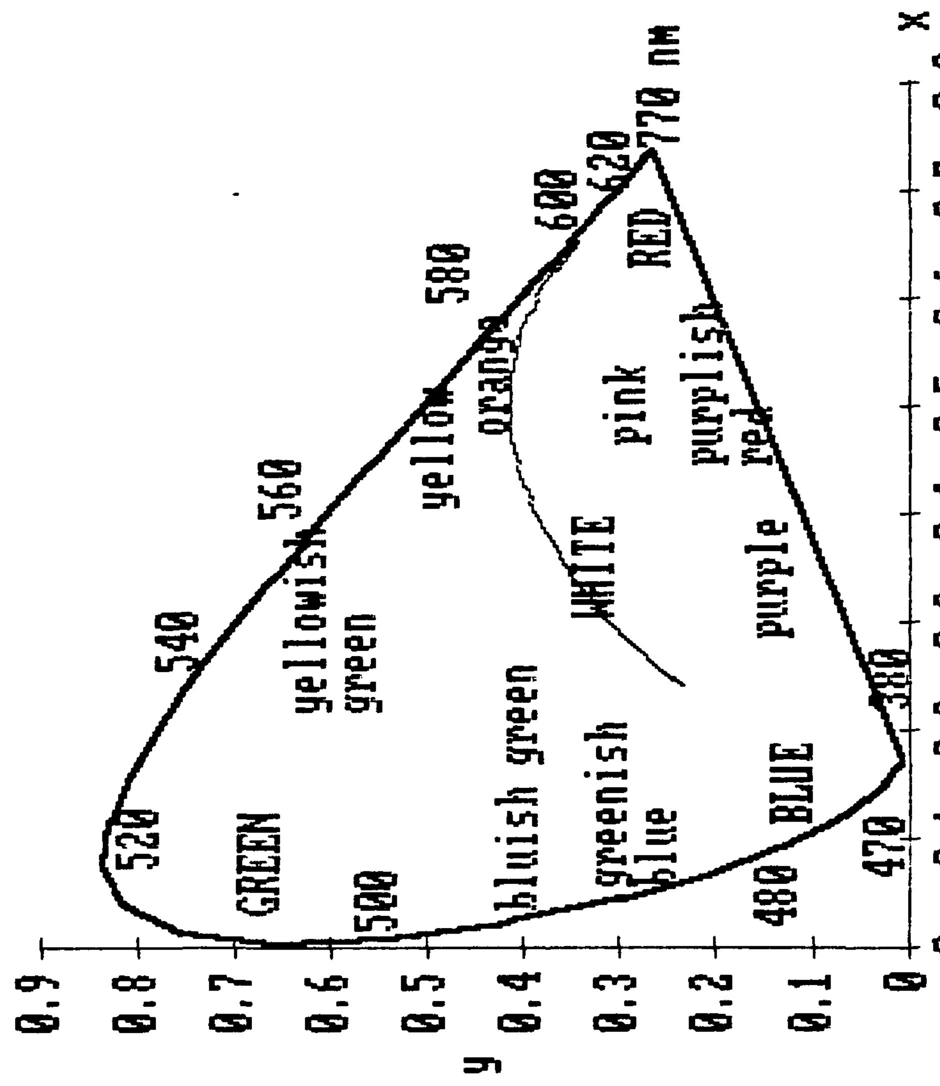

Figure 1. Kelly Chart of CIE Chromaticity Diagram

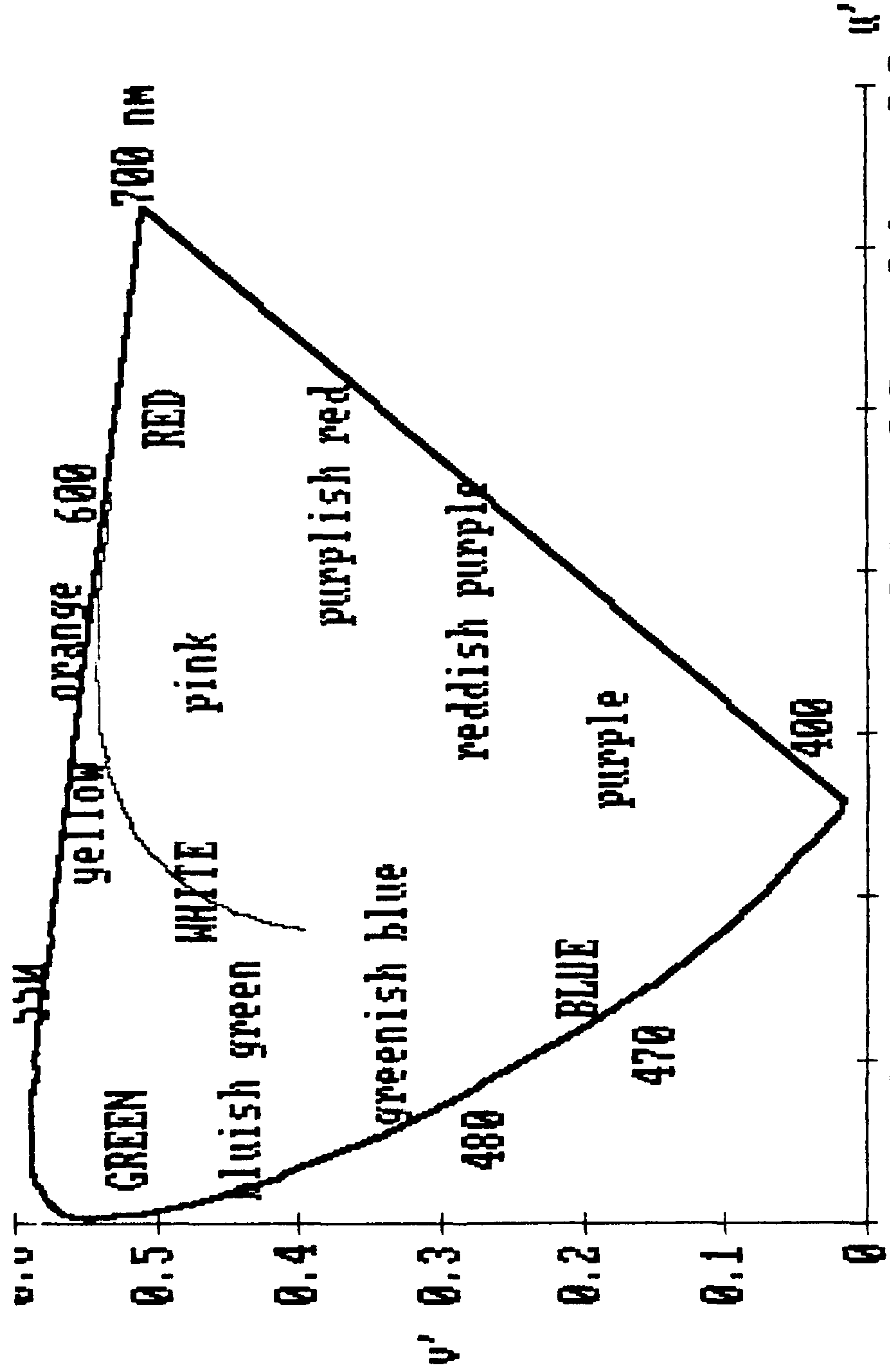

Figure 2. Kelly Chart of UCS Chromaticity Diagram

AMBIENT ILLUM fc:	ENTER: FILTER TRANS:	REFLECTIVITY:	lux:
8,000	21.5%	28.0%	86080

TO CALCULATE:	BACKGROUND LUMINANCE fL	cd/m^2 (nits)
	104	355

COLOR	ENTER: LUMINANCE fL	TO CALCULATE: CONTRAST RATIO	SHADES	MODLTN
GREEN	114.0	2.10	3.1	0.36
RED	77.0	1.74	2.6	0.27
BLUE	60.0	1.58	2.3	0.22
YELLOW	114.0	2.10	3.1	0.36
CYAN	75.0	1.72	2.6	0.27
MAGENTA	74.0	1.71	2.6	-0.26
WHITE	130.0	2.26	3.3	0.39

COLOR	ENTER: CONTRAST RATIO	TO CALCULATE: LUMINANCE fL	SHADES	MODLTN
GREEN	1.00	0.0	1.0	0.00
RED	2.00	103.5	3.0	0.33
BLUE	3.00	207.1	4.2	0.50
YELLOW	4.00	310.6	5.0	0.60
CYAN	5.00	414.2	5.6	0.67
MAGENTA	6.00	517.7	6.2	0.71
WHITE	7.00	621.3	6.6	0.75

ENTER CHROM COORD:	x	y	SATURATN
GREEN	0.3000	0.5900	0.2589
RED	0.6530	0.3230	0.3199
BLUE	0.1500	0.0600	0.3291
YELLOW	0.4680	0.4630	0.1870
CYAN	0.1930	0.2067	0.1890
MAGENTA	0.3220	0.1490	0.1846
WHITE	0.3150	0.2740	0.0621

TO CALCULATE:	u'	v'	SATURATN
GREEN	0.1266	0.5601	0.1205
RED	0.4689	0.5219	0.2629
BLUE	0.1754	0.1579	0.3177
YELLOW	0.2457	0.5469	0.0812
CYAN	0.1515	0.3652	0.1235
MAGENTA	0.3108	0.3236	0.1805
WHITE	0.2227	0.4358	0.0398

Table 1. Color Display Luminance, Contrast, and Chromaticity

COLOR DIFFERENCES

When using color for the coding of display information, care should be given in selecting pairs of colors that can be easily discriminated when one is superimposed on the other. For example, a green foreground (target) should not be placed over a green background (surround). Although this example is obvious, some pairs of colors, even though they are different are not as discriminable as other pairs. Table 3 presents a figure of merit of color differences which includes both luminance and color contrast in the computation. This measure is called the index of discrimination (ID). The chromaticity coordinates (in u', v' space) and the luminance contrast ratio of the color pairs are the inputs to the equations. The greater the resulting ID the easier the pairs of colors are discriminated and therefore the better it is to use the two colors superimposed for coding the foreground and background. In the example shown in Table 3, red/blue is the most discriminable pair, and yellow/white is the least discriminable. These pairings are shown in Figure 5. It should be kept in mind that this measure is dependent on the specific chromaticity of the color, which means that the saturation level is also important. For example, a pale color such as pink is less discriminable from white than a purer red would be. Also, all of the colors in this example were assigned the same luminance level (100). If the colors also differed in luminance, the ID numbers would be greater.

Another, more common, measure of color difference is delta E*. Table 4 shows the input chromaticity coordinates, luminance values (Y), maximum display luminance (Yn), and intermediate values (L*, U*, and V*). The delta E* values ranged from 117 for yellow/white to a maximum of 485 for red/blue. In this example, different luminance values were given to the different colors. By doing this, the relative rankings remain the same, but the magnitude of the delta E* values are changed. To ensure discriminability, a conservative approach is to use only the color pairs above the average (in this case 268). All the pairs extending above the line in Figure 6 should have enough color difference to be adequately discriminated.

Figure 7 shows the primary display colors recommended by Silverstein and Merrifield (1981). Any color whose chromaticity coordinates lie on a line between two phosphor primaries (red, green, or blue) can be produced by the mixture of the colors of the two phosphors. For example, yellow (or amber) can be produced by mixing the colors of the red and green phosphors. In addition, a triangle, which is formed by the chromaticity coordinates of the three phosphor primaries, contains within it all the possible colors that can be produced by the mixture of these three primaries. This triangle is known as the palette or gamut of colors that can be produced by a particular set of primaries. The farther apart (and more saturated) the three phosphor colors, the more different colors can be produced by a particular display. Besides the particular phosphors selected, the size of the palette is also affected by filtering and by the presence of ambient background illumination such as that produced by sunlight.

SUNLIGHT AMBIENT ILLUMINATION

Since the sunlight adds white light to the display colors, the effect of sunlight is to produce less saturated primary colors. Because all of the primary chromaticity coordinates move toward the center of the diagram where the chromaticity of sunlight is located, the palette triangle decreases in size.

As an example, Figure 8 shows the coordinates of colors recommended for a digital map display by Spiker, et al (1986). Superimposed on these points is a triangle representing the palette of colors obtainable with a display in a dark environment. Figure 9 shows what happens to the display palette when the ambient illumination is increased from the dark to 2,000 fc, 5,000 fc, and 10,000 fc. As the triangle becomes smaller, more colors are outside the triangle and therefore less colors can be produced by the display until finally only pale colors and white can be seen at 10,000 fc. This shift in palette size can be attenuated to some degree by the proper use of display filters. However, if the

COLOR	x	y	C(x,y)	10^C(x,y)	Lw	Br	Lreq
GREEN	0.300	0.590	-0.06	0.88	100	88	114
RED	0.653	0.323	0.12	1.30	100	130	77
BLUE	0.150	0.060	0.22	1.67	100	167	60
YELLOW	0.468	0.463	-0.06	0.88	100	88	114
CYAN	0.192	0.207	0.13	1.34	100	134	75
MAGENTA	0.321	0.149	0.13	1.35	100	135	74
WHITE	0.313	0.329	-0.00	1.00	100	100	100
PURPLE	0.205	0.088	0.20	1.58	100	158	63

Lw = Luminance of White (6500K)
Br = Brightness of Color Compared to White
Lreq = Luminance Required to Equal Brightness of White
C(x,y) = Conversion Factor
10^C(x,y) = 10 raised to the power of the conversion factor

Table 2. Luminance to Brightness Conversion

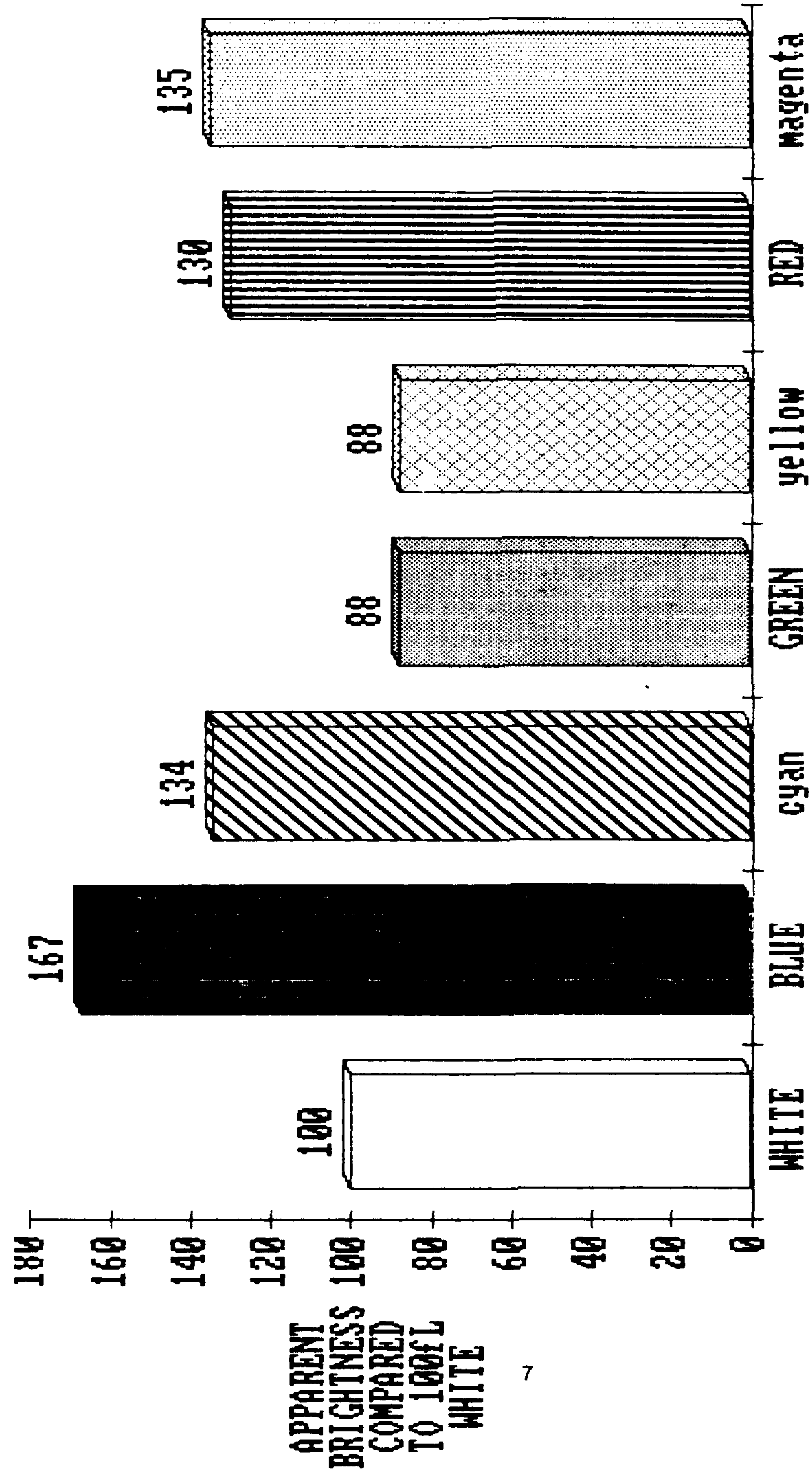

Figure 3. Brightness Compared to 100 fL White

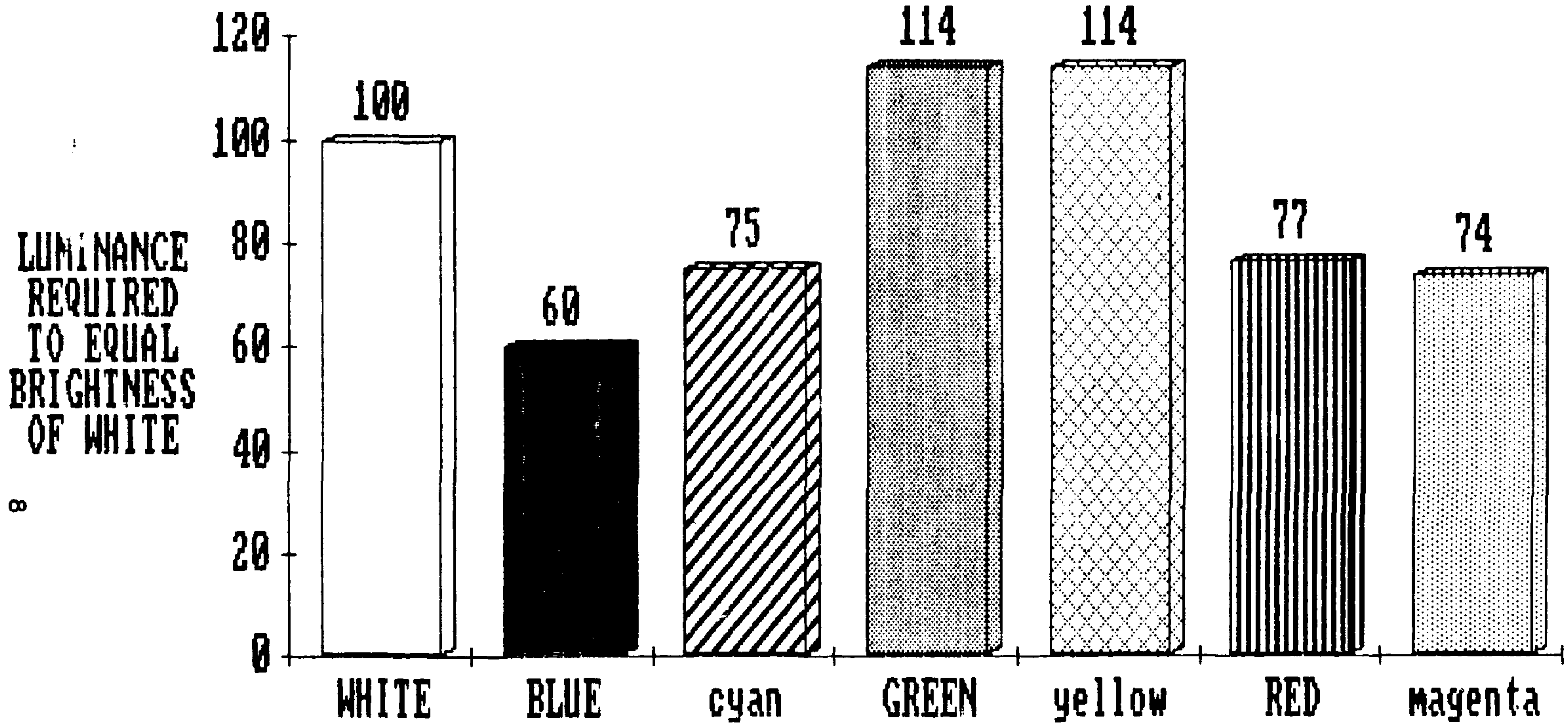

Figure 4. Luminance Required to Equal Brightness of White

ENTER: COLOR	x	y	TO CALCULATE: u'	v'	ENTER: Ldisp	BACKGRN LUM
GREEN	0.300	0.590	0.127	0.560	100.0	75
RED	0.653	0.323	0.469	0.522	100.0	
BLUE	0.150	0.060	0.175	0.158	100.0	
YELLOW	0.468	0.463	0.246	0.547	100.0	
CYAN	0.192	0.207	0.151	0.365	100.0	
MAGENTA	0.321	0.149	0.310	0.323	100.0	
WHITE	0.313	0.329	0.198	0.468	100.0	

TO CALCULATE:

	ID		ID		ID
GR-RD	2.10	RD-yw	1.37	BL-WT	1.89
GR-BL	2.47	RD-cy	2.16	yw-cy	1.25
GR-yw	0.73	RD-mg	1.55	yw-mg	1.41
GR-cy	1.19	RD-WT	1.68	yw-WT	0.56
GR-mg	1.82	BL-yw	2.41	cy-mg	1.00
GR-WT	0.71	BL-cy	1.27	cy-WT	0.69
RD-BL	2.85	BL-mg	1.30	mg-WT	1.11
AVER=	1.50	MAX=	2.85	MIN=	0.56

RD = RED　　yw = yellow
GR = GREEN　　cy = cyan
BL = BLUE　　mg = magenta
WT = WHITE　　Ldisp = Display Luminance

Table 3. Index of Discrimination (ID)

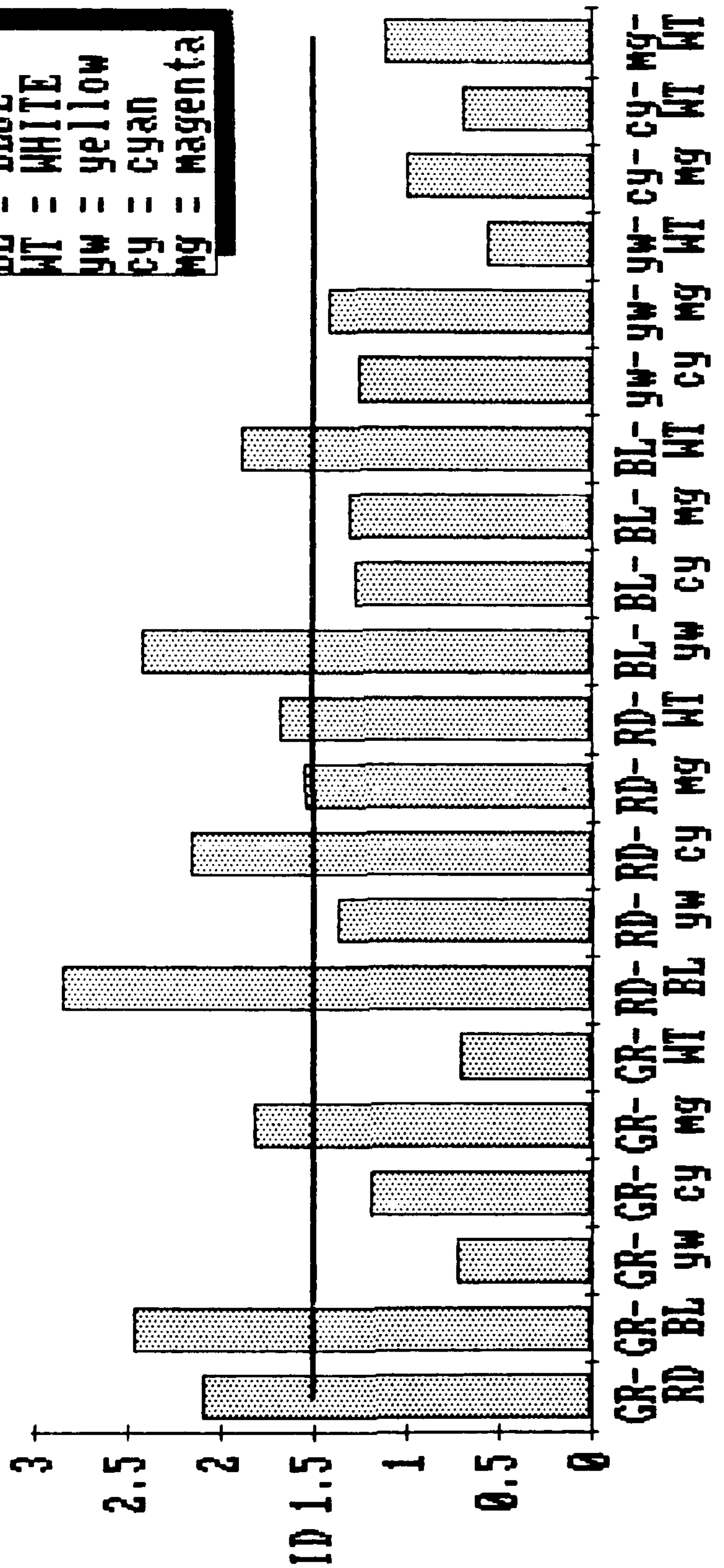

Figure 5. Index of Discrimination

COLOR	u'	v'	Y=	L*	U*	V*	Yn=
GREEN	0.1266	0.5601	114	98.03	-91.02	117.41	120
RED	0.4689	0.5219	77	84.05	296.05	58.90	
BLUE	0.1754	0.1579	60	76.07	-22.31	-306.66	
YELLOW	0.2458	0.5468	114	98.03	60.93	100.43	
CYAN	0.1506	0.3653	75	83.18	-51.27	-111.06	
MAGENTA	0.3093	0.3239	74	82.74	119.75	-154.95	
WHITE	0.1978	0.4684	130	103.14	-0.28	0.50	

delta E*		delta E*		delta E*			
GR-RD	392	RD-yw	239	BL-WT	309	GR =	GREEN
GR-BL	430	RD-cy	387	YW-cy	240	RD =	RED
GR-yw	153	RD-mg	277	yw-mg	263	BL =	BLUE
GR-cy	232	RD-WT	303	yw-WT	117	yw =	yellow
GR-mg	345	BL-yw	416	cy-mg	177	cy =	cyan
GR-WT	148	BL-cy	198	cy-WT	124	mg =	magenta
RD-BL	485	BL-mg	208	mg-WT	197	WT =	WHITE
Min =	117	Max =	485	Average =	269		

Y = LUMINANCE OF COLOR TO BE COMPARED
Yn = MAXIMUM DISPLAY LUMINANCE
delta E* = COLOR DIFFERENCE (LUMINANCE & CHROMATICITY)
L* = 116(Y/Yn)^1/3-16
U* = 13L*(u'-u'n)
V* = 13L*(v'-v'n)
u'n = .198
v'n = .468

Table 4. Color Differences (delta E*)

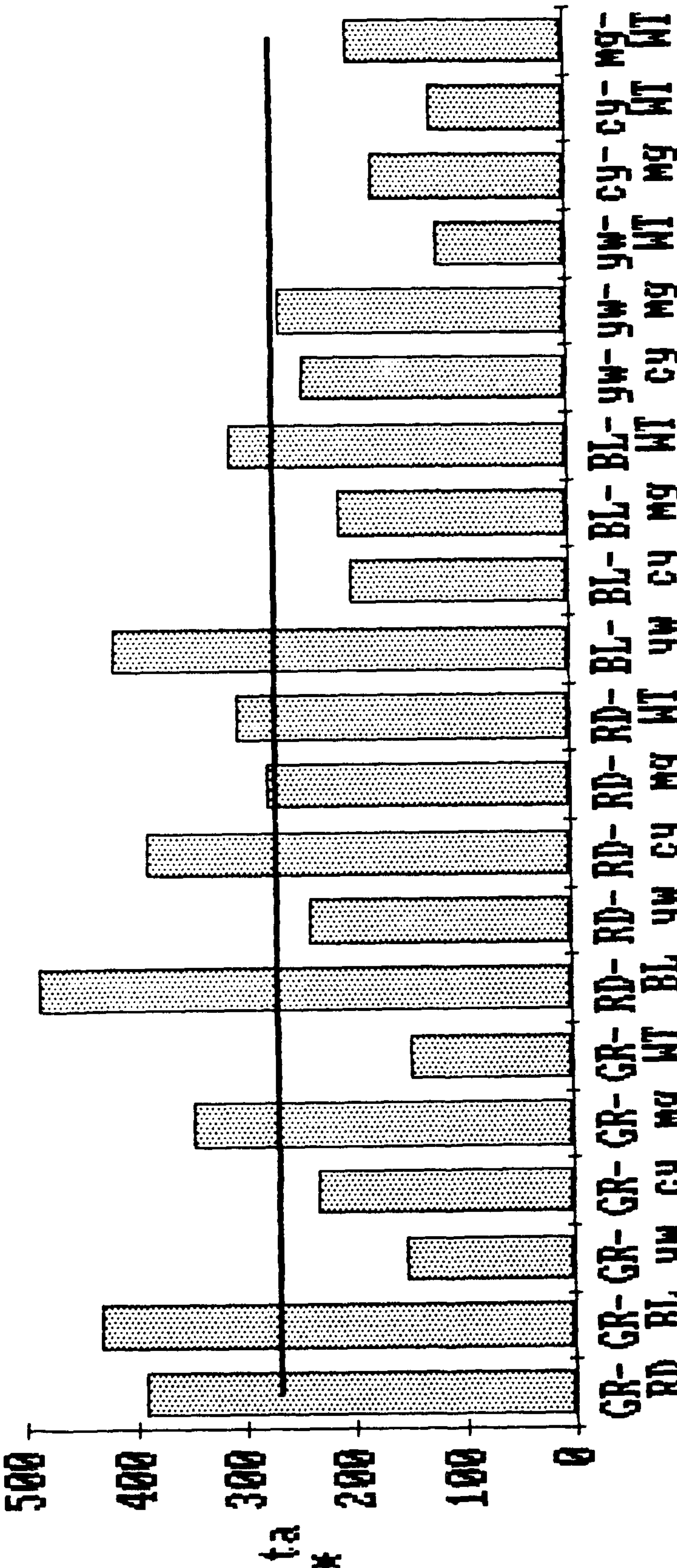

Figure 6. Color Difference Using delta E*

display primary colors that are selected initially are desaturated or pastel, then only a relatively low level of sunlight illumination will cause this problem.

CHROMATICITY REQUIREMENTS

In order to determine an appropriate criterion for the selection of chromaticity coordinates of the six primaries plus white, a complication was made of the color requirements and recommendations from various sources (specifications, standards, manufacturers' data, and technical documentation). The data were described statistically, and the results were transformed into u', v' color space. Table 5 presents the data and statistics. The sources listed have been coded with the letters of the alphabet because of the possible proprietary nature of some of the data. Figures 10 and 11 are summaries of these data. Using the means computed from the data, a color palette triangle was constructed. Figure 12 shows the triangle in both x, y and u', v' color space. Figure 13 shows the mean and plus or minus one standard deviation for each primary and white. One standard deviation was selected as a limit to the chromaticity space since three standard deviations are equal to approximately one jnd (just noticeable difference). In this case, color uniformity and not color discriminability, is important. In Figures 14 and 15 these points are used as vertices to construct rectangles for each primary color. In specifying the colors required, therefore, it would be reasonable and appropriate to limit the chromaticity coordinates to the boundaries of these boxes. However, in order to approximate perceptual uniformity, circles should circumscribe the rectangles in order to produce the color limits of the UCS diagram.

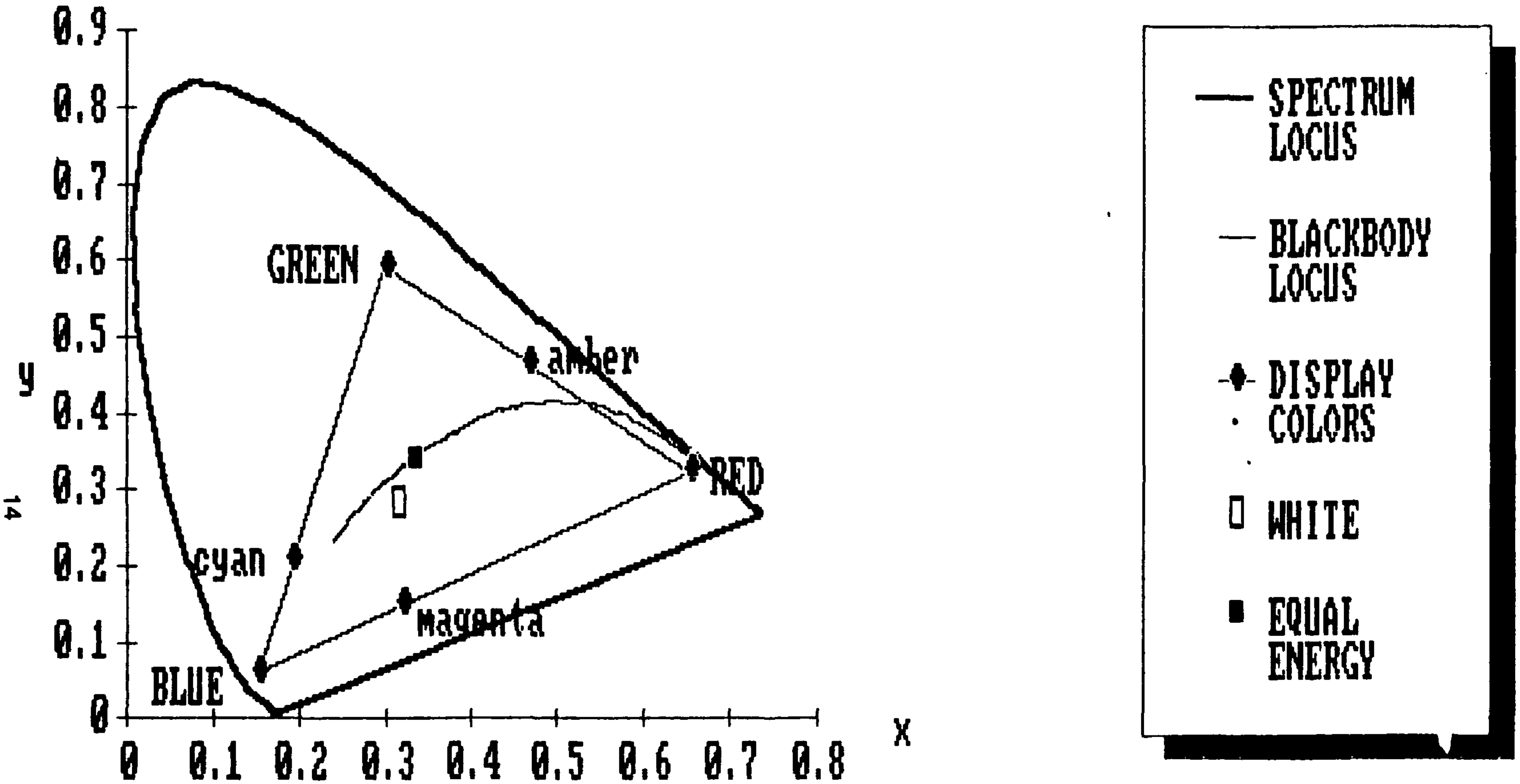

Figure 7. Color Requirements from Silverstein & Merrifield

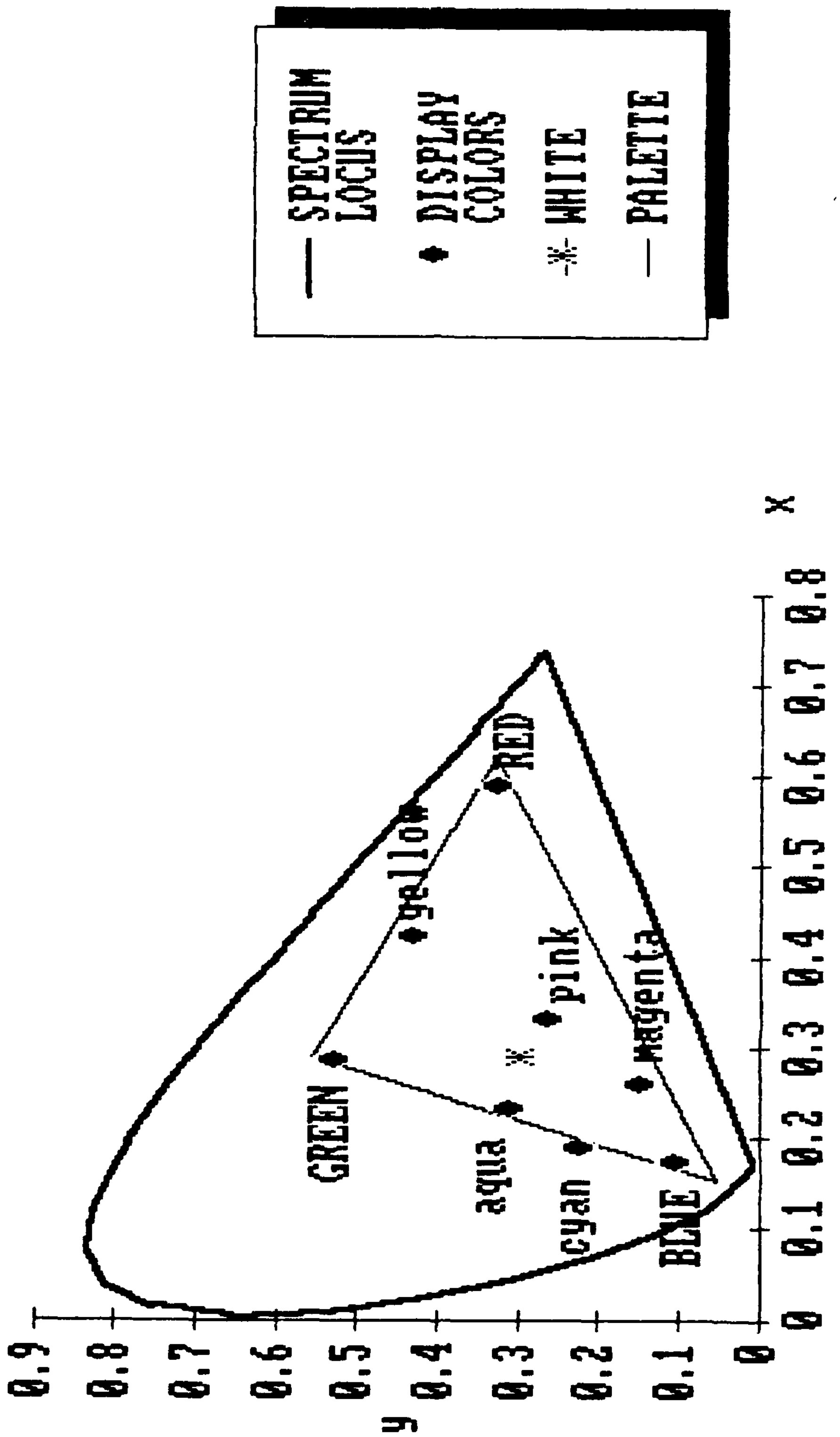

Figure 8. CRT Map Colors (dark ambient environment)

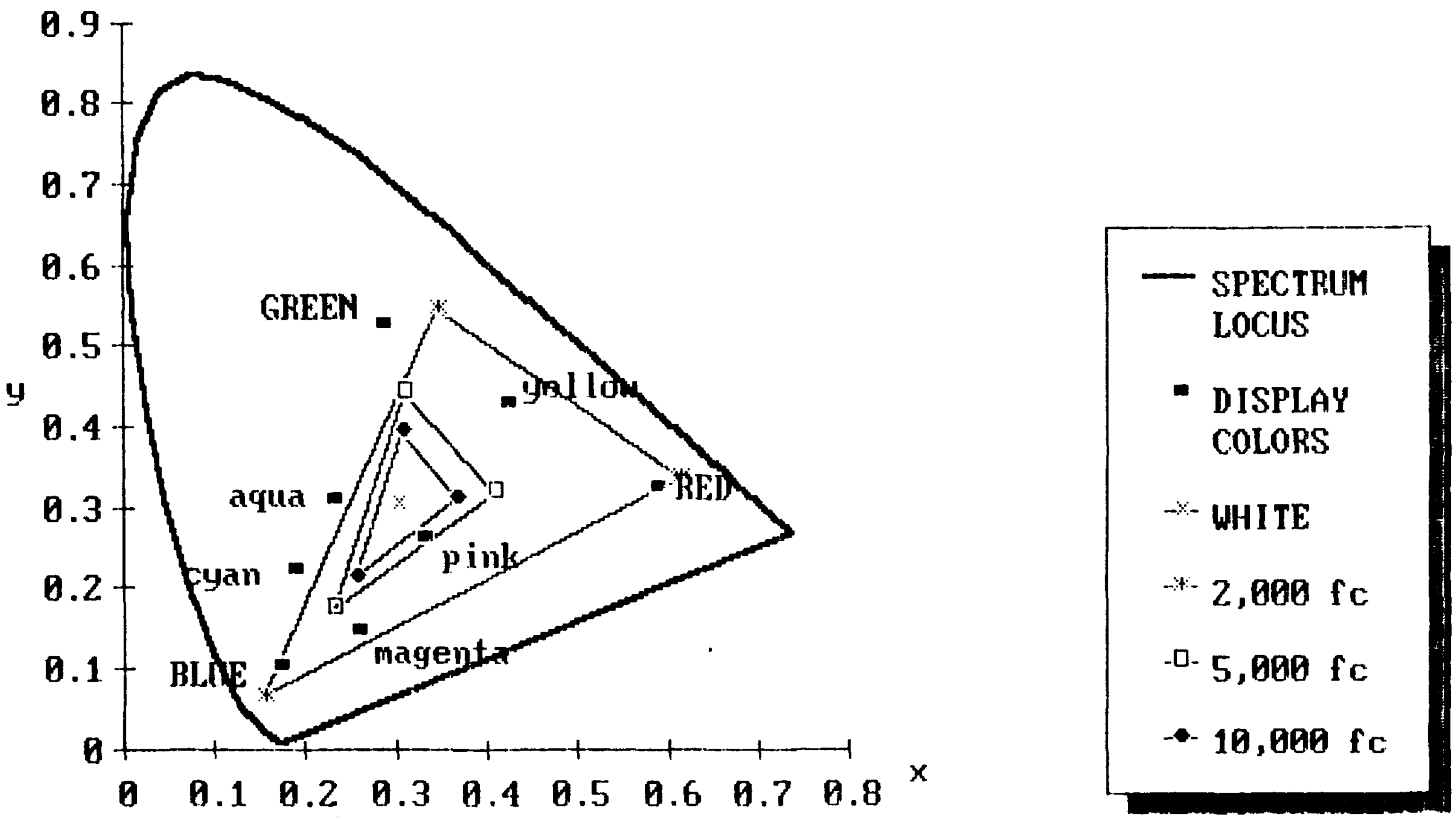

Figure 9. CRT Map Colors (daylight environment)

DATA SOURCE	RED x	RED y	GREEN x	GREEN y	BLUE x	BLUE y
A	0.588	0.320	0.284	0.524	0.171	0.100
B	0.560	0.318	0.278	0.502	0.175	0.101
C	0.653	0.323	0.300	0.590	0.150	0.060
D	0.626	0.340	0.333	0.556	0.150	0.065
E	0.714	0.386	0.295	0.454	0.144	0.057
F	0.737	0.440	0.345	0.559	0.150	0.060
G	0.608	0.350	0.286	0.605	0.150	0.066
H	0.622	0.347	0.300	0.602	0.148	0.065
I	0.610	0.340	0.280	0.590	0.152	0.063
J	0.610	0.350	0.290	0.600	0.150	0.060
K	0.613	0.335	0.343	0.544	0.153	0.064
L	0.658	0.342	0.229	0.599	0.150	0.049
M	0.562	0.312	0.321	0.473	0.172	0.065
N	0.643	0.323	0.306	0.586	0.154	0.061
O	0.670	0.330	0.210	0.710	0.140	0.080
P	0.605	0.347	0.297	0.587	0.153	0.063
Q	0.610	0.365	0.268	0.594	0.162	0.073
R	0.478	0.426	0.185	0.624	0.153	0.045
S	0.631	0.365	0.294	0.609	0.161	0.140
T	0.630	0.344	0.277	0.597	0.150	0.075
U	0.680	0.320	0.280	0.600	0.150	0.070
V	0.675	0.325	0.220	0.680	0.130	0.080
MINIMUM	0.478	0.312	0.185	0.454	0.130	0.045
MAXIMUM	0.737	0.440	0.345	0.710	0.175	0.140
RANGE	0.259	0.128	0.160	0.256	0.045	0.095
MEAN	0.627	0.348	0.283	0.581	0.153	0.071
STD DEV	0.053	0.032	0.040	0.057	0.010	0.020
MEAN-STD DEV	0.573	0.315	0.243	0.524	0.143	0.051
MEAN+STD DEV	0.680	0.380	0.323	0.638	0.163	0.091
MEAN u',v'	0.423	0.529	0.120	0.556	0.173	0.180
MN-SD u',v'	0.406	0.503	0.110	0.536	0.172	0.138
MN+SD u',v'	0.439	0.552	0.129	0.574	0.173	0.217
DISTANCE TO	0.030		0.022		0.042	
MEAN u',v'	0.028		0.020		0.037	

PRIMARY CHROMATICITY COORDINATES

Table 5. Compilation of Color Requirements/Recommendations

DATA SOURCE	CYAN x	CYAN y	MAGENTA x	MAGENTA y	YELLOW x	YELLOW y	WHITE x	WHITE y
	PRIMARY CHROMATICITY COORDINATES							
A	0.187	0.220	0.257	0.143	0.422	0.425	0.291	0.306
B	0.220	0.299	0.264	0.154	0.431	0.418	0.280	0.311
C	0.192	0.207	0.321	0.149	0.468	0.463	0.315	0.274
D								
E								
F								
G								
H								
I								
J								
K								
L							0.313	0.328
M								
N								
O							0.333	0.333
P							0.309	0.313
Q					0.442	0.478	0.324	0.307
R	0.164	0.261	0.259	0.170	0.300	0.546	0.233	0.322
S							0.317	0.311
T	0.201	0.284	0.326	0.177	0.454	0.469	0.334	0.317
U								
V								
MINIMUM	0.164	0.207	0.257	0.143	0.300	0.418	0.233	0.274
MAXIMUM	0.220	0.299	0.326	0.177	0.468	0.546	0.334	0.333
RANGE	0.056	0.092	0.069	0.034	0.168	0.128	0.101	0.059
MEAN	0.193	0.254	0.285	0.159	0.419	0.467	0.305	0.312
STD DEV	0.018	0.036	0.031	0.013	0.055	0.042	0.029	0.015
MEAN-STD DEV	0.175	0.218	0.254	0.146	0.364	0.425	0.276	0.297
MEAN+STD DEV	0.211	0.290	0.316	0.171	0.475	0.508	0.334	0.328
MN u',v'	0.136	0.404	0.263	0.329	0.216	0.541	0.199	0.458
M-SD u',v'	0.132	0.373	0.240	0.309	0.198	0.519	0.184	0.445
M+SD u',v'	0.139	0.431	0.286	0.349	0.233	0.561	0.213	0.471
DISTANCE TO	0.031		0.031		0.029		0.020	
MEAN u',v'	0.027		0.030		0.026		0.019	

Table 5. Compilation of Color Requirements/Recommendations (cont.)

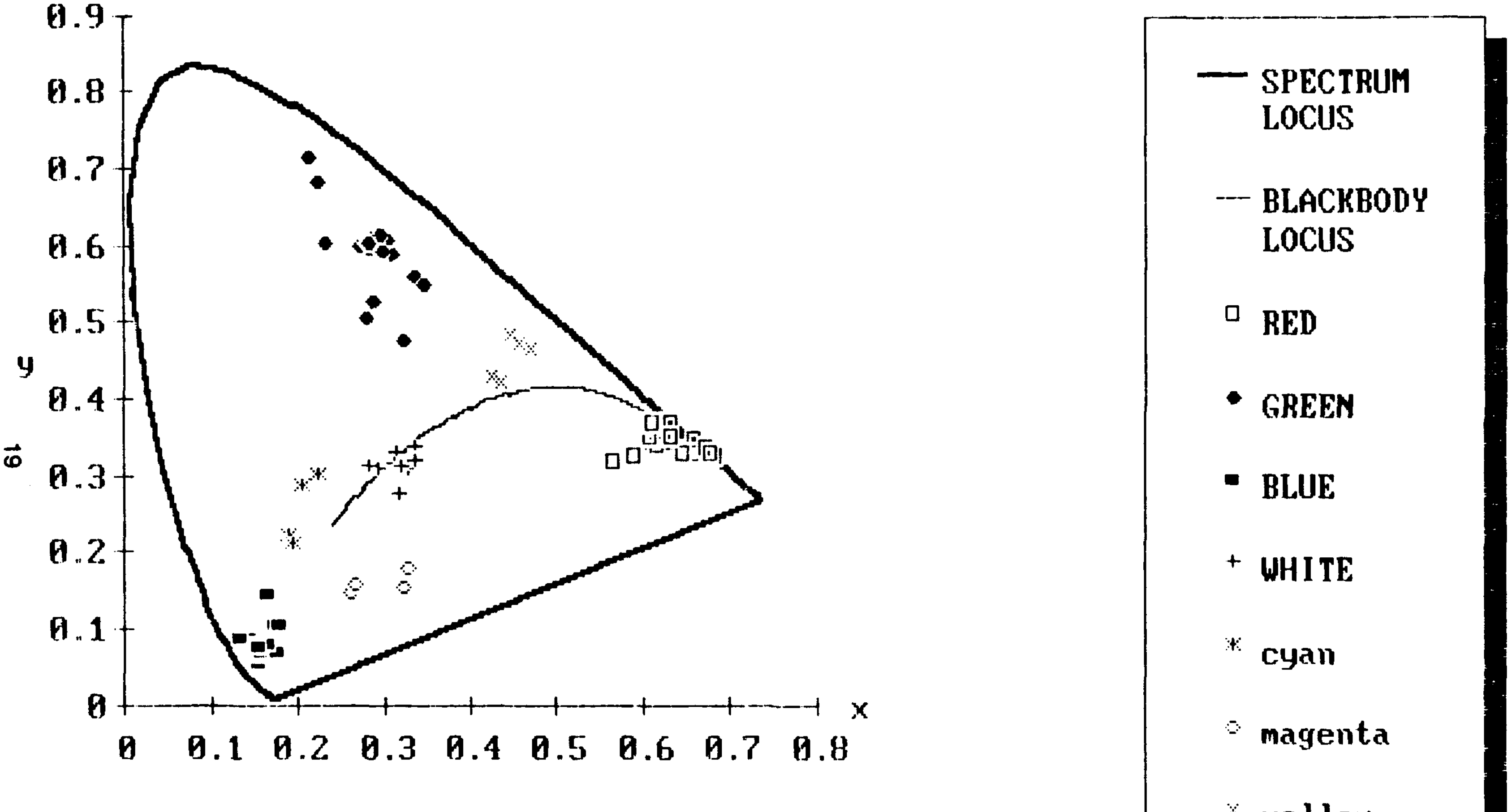

Figure 10. Summary of Color Requirements/Recommendations

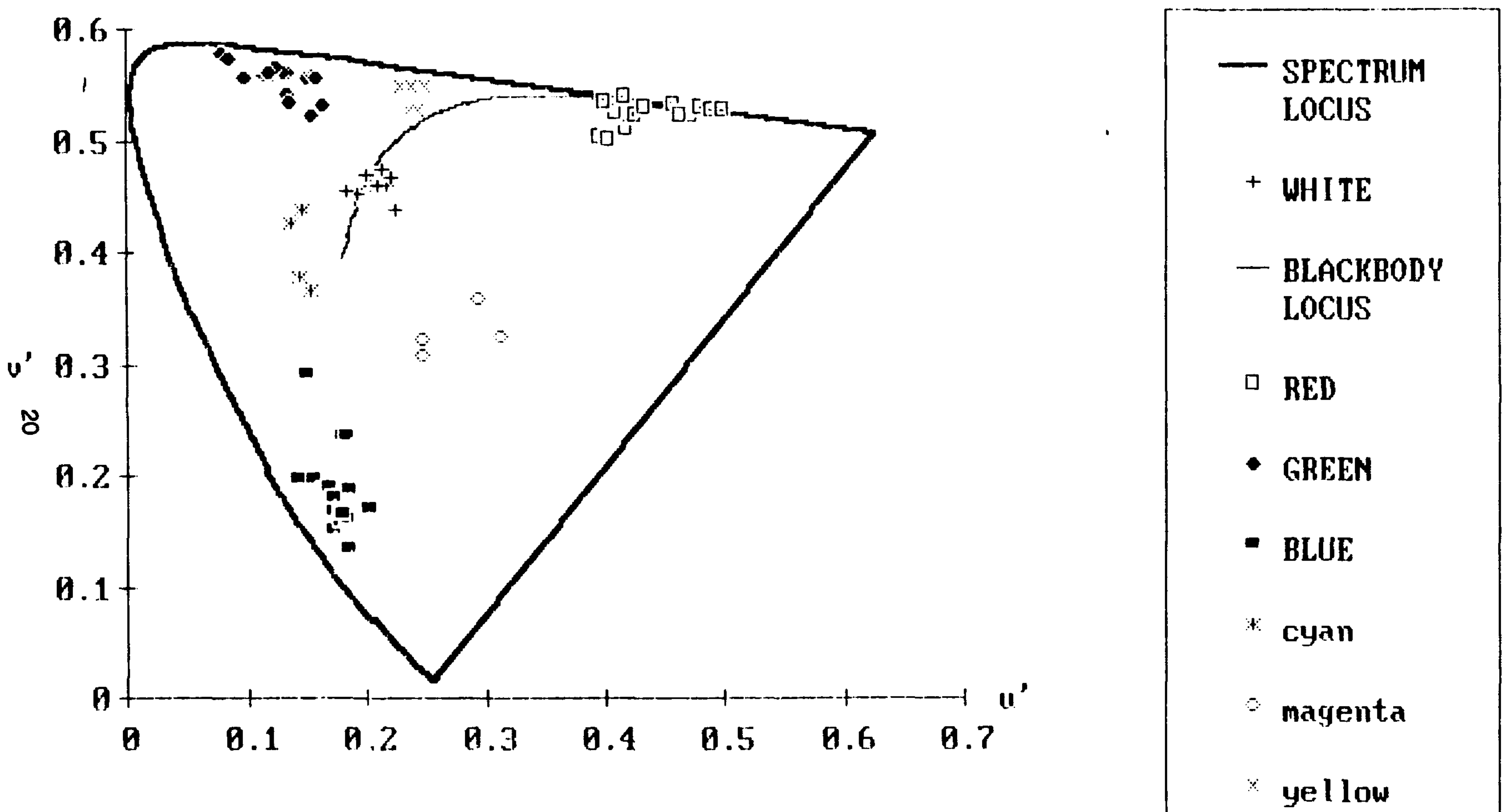

Figure 11. Summary of Color Requirements/Recommendations (UCS)

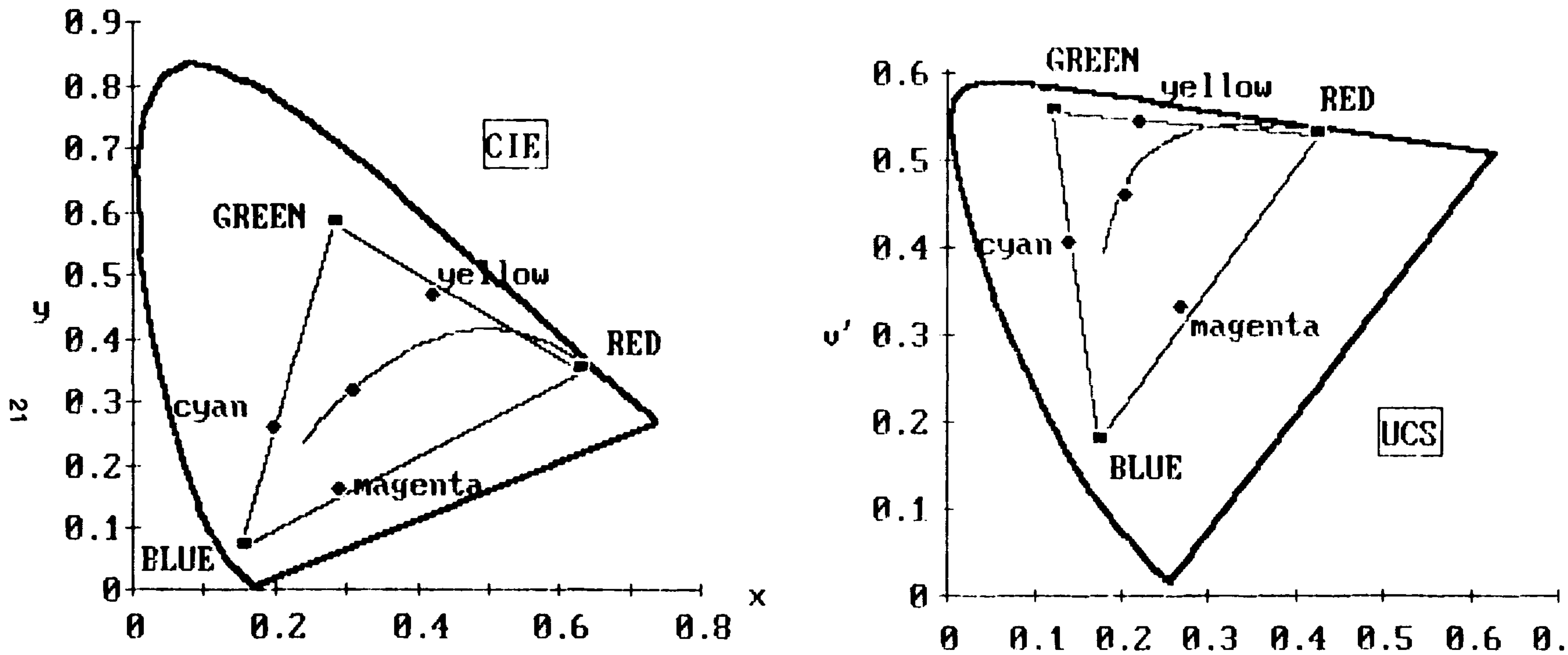

Figure 12. Means of Primaries (CIE & UCS)

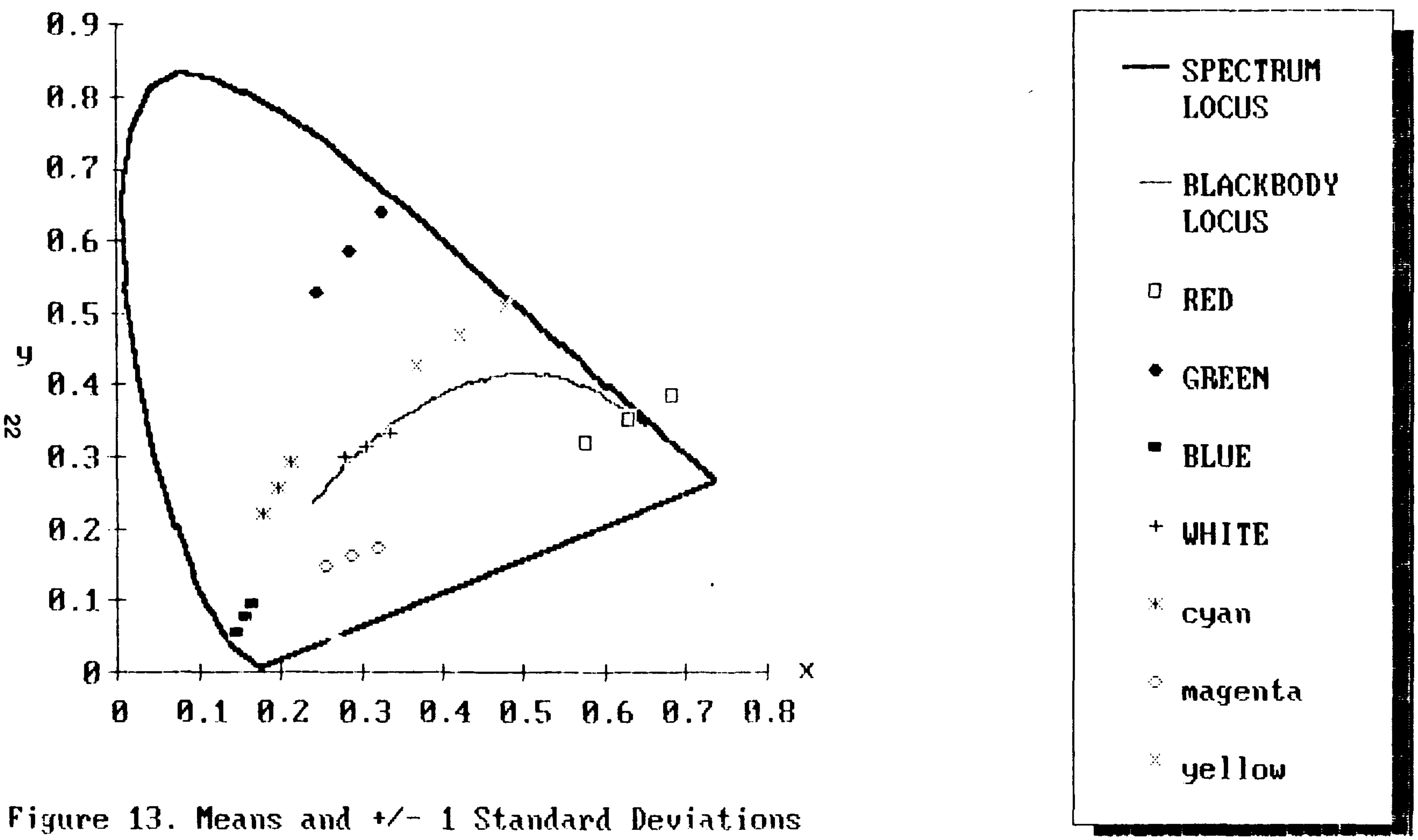

Figure 13. Means and +/- 1 Standard Deviations

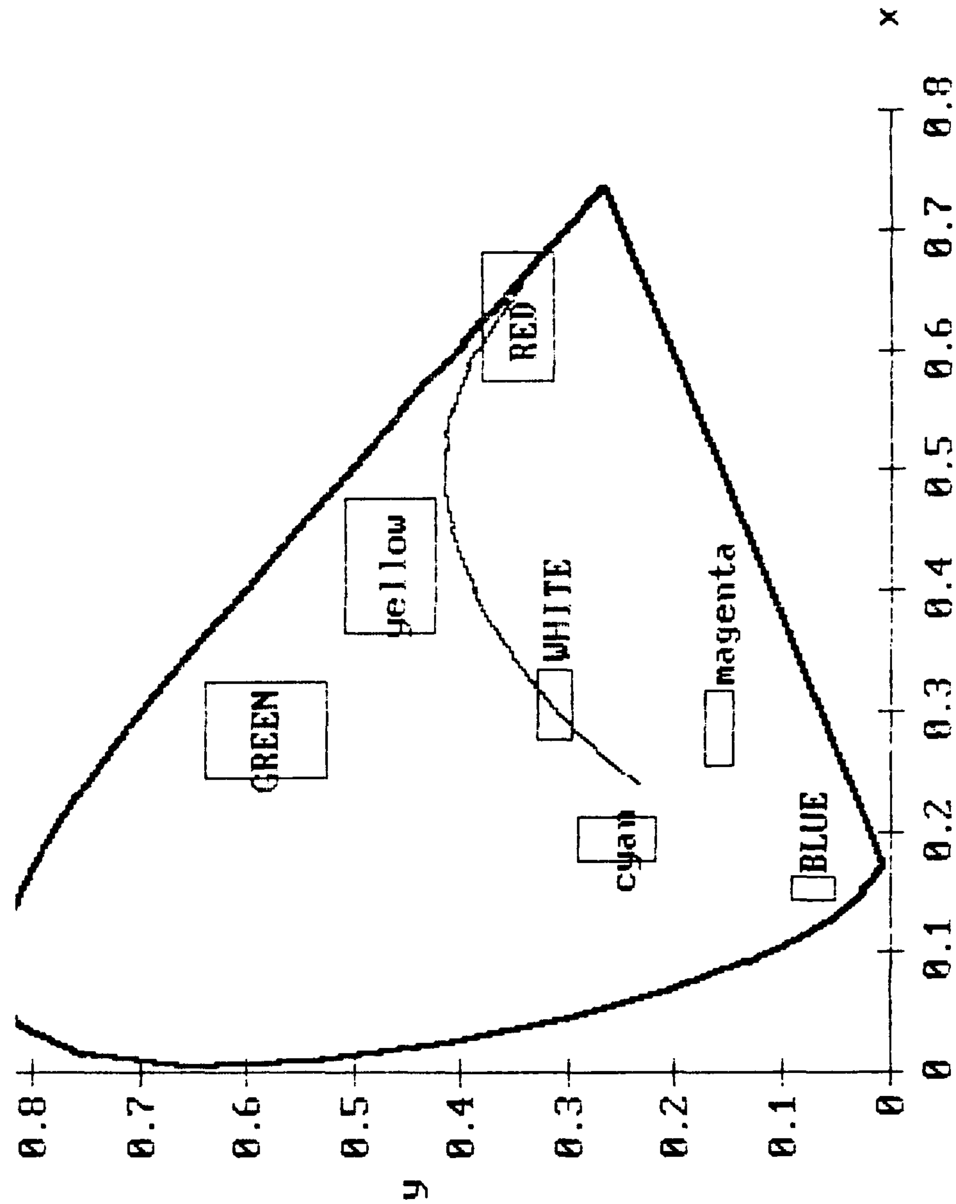

Figure 14. +/- 1 Standard Deviation Color Areas (CIE)

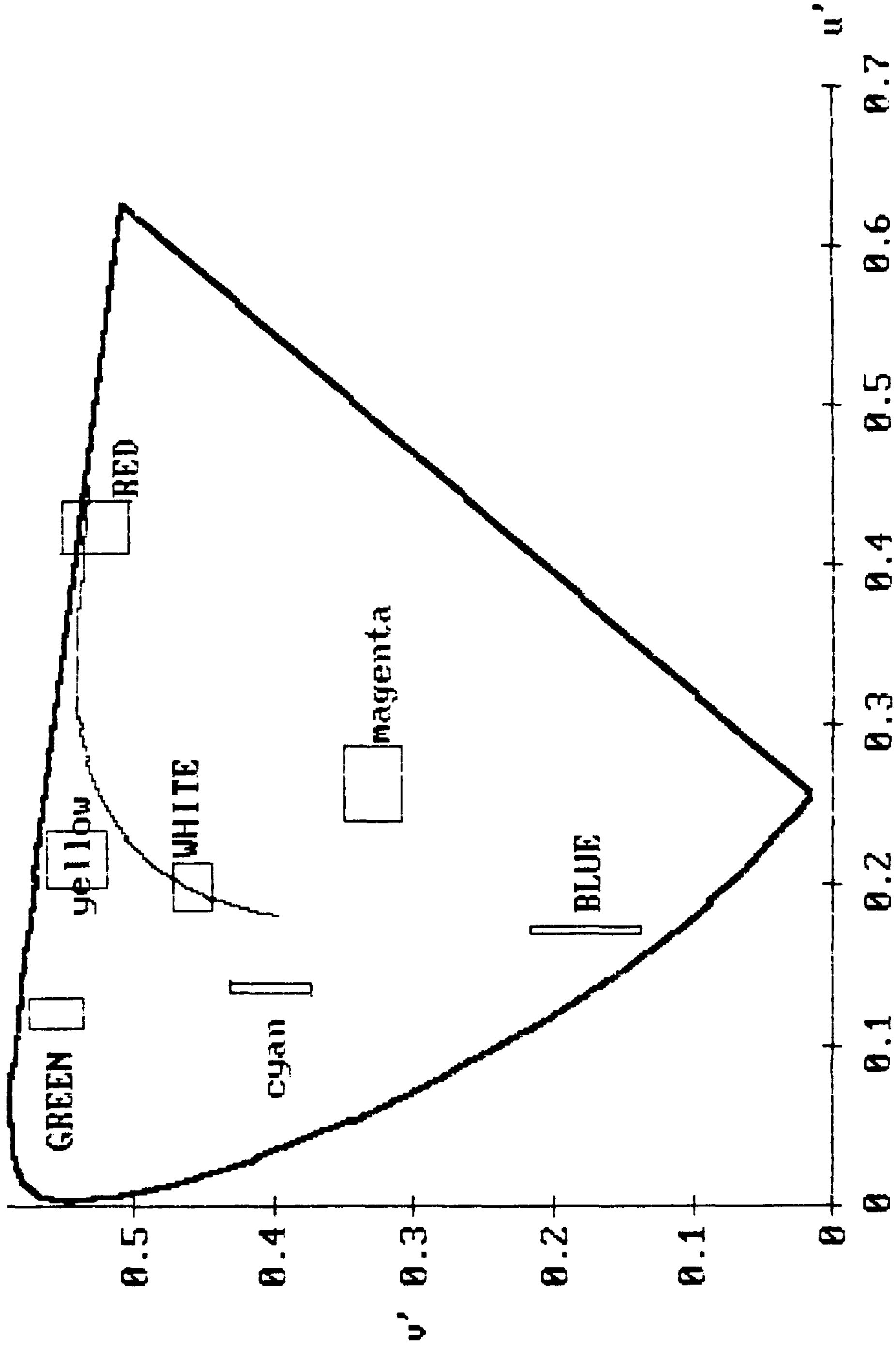

Figure 15. +/- 1 Standard Deviation Color Areas (UCS)

SUMMARY AND CONCLUSIONS

Color coding of display information, when used properly, can decrease the operator's workload in performing certain visual tasks. In order to be effective, the luminance levels and chromaticity coordinates (with limits) of the colors need to be specified based upon human factors design principles.

Color luminance, depending on the display background luminance, should be great enough to provide a contrast ratio of at least 1.5:1. If shades (for example, shades of gray or green) are required; then a greater contrast ratio and luminance level, (determined by the number of shades) should be provided. Another consideration for specifying luminance levels is the requirement for uniform brightness. This requirement can be accomplished by providing different luminance levels for each color based upon the conversion function presented in Table 2.

The maximum luminance values for each of the primaries (especially red and blue) should not be constrained by the proportions needed for white. For example, if 100 fL of white requires a mixture of 59 fL green, 30 fL red and 11 fL blue, red should not be limited to a maximum luminance of 30 fL when used by itself. For sunlight ambient illumination, the higher the display luminance, the better will be the visibility.

Also to be considered is the requirement to use together colors that can be easily discriminated. Metrics such as delta E* can be helpful in determining color differences. In addition, primary colors should be as saturated as possible in order to provide a sufficiently large color palette. Also, in order to provide uniformly appearing colors, the boxes suggested by Figures 14 and 15 should be used to formulate chromaticity limits.

This report presented only some of the important design criteria that should be considered when using color to code information for aircraft displays. Other issues that will be addressed in future studies include: night vision imaging system compatibility, the use of pseudocolor for sensor imagery, color filled versus color outlined symbols, the use of black for color contrast, and symbol size requirements for different colors.

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